Concurrent Multiscale Hybrid Topology Optimization for Light Weight Porous Soft Robotic Hand with High Cellular Stiffness

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Abstract. This article's primary objective is to investigate the topological optimization of soft robotic grips, using hybrid topology optimization. For the goal of creating light weight and porous soft gripper designs. This task is constituted of two design problem, for which we developed a hybrid SIMP-ESO approach, where SIMP solves the macroscale and ESO solves the microscale optimization. We formulate the microstructure as the maximum allowable young moduli that can be achieved for high weight minimization for the microscale, considering the case of orthotropic materials. To examine the performance of the suggested method we evaluate several macro scale and microscale combinations. The results attained robust and 3D printable designs.

Keywords: Soft robotics · Porous structure · Multiscale · Hybrid topology optimization

1 Introduction

Soft robotics has been the subject of a strong interest in the last few years, both from researchers and industry. Roboticist is considered as a potentially whole new class of machines that perform better in the real world and are more versatile [1–4]. Soft robotics is intending to make robots that are, flexible, and soft like biological organisms. Like natural tissue, the main frame of a soft robot is distributing the energy to attain the action so it is deformed due to the action based on its reaction to the action fields rather than relying fully on linkage movements and gears as in traditional robotics. In the other words, it is seeking to expand the scope of robotics beyond the limited scope of dynamic rigid bodies. Designing an ultralightweight and stiff soft robotic gripping hand that attains gripping with a single actuation point is the main goal of this paper. This task is approached by adopting two aspects; the first one is implementing a structure that redistributes the strain energy to attain a precise prescribe displacement control. The second aspect is to make it a porous structure, to achieve extreme light weighting with maintaining high performance. Furthermore, the pore will be designed to have the maximum martial's property (i.e., axial and/or shear stresses resilience). In order to attain such structure, non-parametric

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optimization is utilized in this research. One of the most efficient non-parametric optimization methods for attaining profound designs with the extremum of the user-defined objective is topology optimization. Through the discretization of the design space, this general technique applies conventional optimization algorithms to the topology of structures. In order to solve the optimization problem for static loading scenarios, load steps, design variables, responses, constraints, and objectives must be defined [5–8]. Associated with additive manufacturing, topologically optimized structures are shown robust design and showed good performance [9–11]. Furthermore, topology optimization gave the opportunity to create lightweight, highly functional structures.

In order to maximize structural performance to weight ratio while satisfying various design requirements, structural topology optimization seeks to identify the best and most reliable material distribution within the design domain. One of the earliest continuum topology optimization techniques for developing compliant systems was the homogenization approach. This method converts computationally expensive structural topology optimization problems into an effective multiscale optimization problem by introducing a material density function in each discretized element, which is made up of an infinite number of randomly distributed holes. The homogenization theory is used to determine the mechanical properties of materials.

There are two different approaches to adding microstructures: those based on rank laminate composites and those based on hollow microcells. In the former case, the homogenization equation can be solved analytically, whereas in the latter case, the homogenization problem is frequently solved using numerical techniques. With the homogenization method, theoretical structural performance can be mathematically constrained [12]. Ananthasuresh et al. [13] has extended the homogenization to perform compliant mechanisms designs. However, because the resulting mechanisms are not flexible enough, the results appear to be a mean compliance design rather than a compliant mechanism design. As a result, Nishiwaki et al. [14] developed a homogenization-based topology optimization method for the design of compliant mechanisms that includes flexibility. In their method and in order to effectively describe the flexibility, the creation of a multi-objective function using mutual mean compliance was used. SIMP (solid isotropic microstructure with penalization) has been used to design compliant mechanisms as a direct descendant of the homogenization method [15–18]. Additionally, the evolutionary structural optimization (ESO) method was developed on the straightforward tenet of gradually removing wasteful material from a structure in order to get the optimum structure conceivable.

The fundamental tenet of ESO is the elimination of the so-called "inefficient material" directly from the building in order to create the best design and it is firstly introduced by Min and Steven [19]. The cost function sensitivity is used to update the decision variables [20, 21]. Updates are based on the element sensitivity number that is generated by differentiating the objective function so that the elemental sensitivity and zero are identical for solid and soft elements, respectively. And as for SIMP, ESO was investigated for designing compliant mechanisms [22–25]. Due to the challenges in creating robust designs, the multiscale compliant mechanism has received little attention from researchers. In addition, due to the fluctuating effective properties for the grayscale elements at the start of the optimization process, the grayscale nature of such a problem when it is optimized using the SIMP method significantly restricts attaining extrema. The research of Sivapuram et al. [26] suggested an improved compliant mechanism optimization using level-set method. The Binary element idea in zero-level-set method was shown to be effective for robust soft compliant mechanism design.

The idea of concurrent multiscale optimization of compliant mechanisms has not been investigated so far. Moreover, the hybrid method of SIMP and ESO has not been implemented in the concurrent design of the multiscale compliant mechanism. n this research, we investigate this idea of hybrid design methods of SIMP for macroscale and ESO for designing microscale to design porous displacement inverter, for robotic grip. We developpe a dedicated finite element model to solve the homogenization for microstructure. We calculate the macrostructure using a different finite element model. The concurrent design function's sensitivity analysis is implemented through the adjoint approach, which significantly lowers the computational cost. We discussed in the second section the mathematical modelling of the multiscale problem. And in Sect. 3 we discuss the studied design cases. Finally, we conclude this study in Sect. 4.

2 The Mathematical Modelling of Concurrent Multiscal Hybrid Topology Optimization

In order to simultaneously optimize the objective function on both the macro $\mathbf{x}_{\mathrm{M}}$ and microscales $\mathbf{x}_m$, concurrent multiscale topology optimization was carried out. Two distinct finite element systems are used to discretize the macro and microscale design domains. For both systems in this paper, we used a bilinear structured mesh. According to Eq. (1), when is equal to 1, the corresponding element is a solid, while when it is zero, the element represents a void.

$$\mathbf{x}_{\mathrm{M}}, \mathbf{x}_{\mathrm{m}} = \begin{cases} 1 & \textit{solid material} \\ 0 & \quad \textit{Void} \end{cases} \tag{1}$$

The utilization of a homogenization approach is required for concurrent design of multiscale problems for two reasons. The effective properties of the macrostructure must first be determined. The microscale objective function is use inverse homogenization to simultaneously create the macrostructure as well as the microstructure. Starting from the investigation for the evaluation of the effective elastic tensor by assuming that the Hooks law.

$$\boldsymbol{\sigma} = \mathbf{E}\varepsilon \tag{2}$$

To evaluate overall (i.e., effective) elastic tensor $\mathbf{E}^{\mathrm{H}}_{ijkl}$ of the representative volume element (RVE) Eq. (3) is used:

$$\mathbf{E}^{\mathrm{H}} = \frac{1}{|V|} \int\limits_{V} \mathbf{E}_{ijqp} \left(\boldsymbol{\varepsilon}_{qp}^{0(kl)} - \boldsymbol{\varepsilon}_{qp}^{*(kl)} \right) dV \tag{3}$$

where $\mathbf{E}_{ijqp}$ is the elastic tensor of the composite materials that consisting the RVE, $\boldsymbol{\varepsilon}_{qp}^{0(kl)}$ is the linearly independent unit strain test [27]. $\boldsymbol{\varepsilon}_{qp}^{*(kl)}$ is characteristic periodic strain which is obtained by solving Eq. (4)

$$\int_{\Omega_m} \mathbf{E}_{ijqp}\boldsymbol{\varepsilon}_{qp}^{*(kl)}\partial\gamma_n dV = \int_{\Omega_m} \mathbf{E}_{ijqp}\boldsymbol{\varepsilon}_{qp}^{0(kl)}\partial\gamma_n dV \tag{4}$$

where $\partial\gamma_n$ is the arbitrary virtual displacement associated with unit strain case. Equation (3) is solved for the three cases of (i.e., kl = 11, 22, 12 respectively), within Eq. (4). On the other hand, the structure compliance in terms of the micro and macro design variables ($\mathbf{x}_{\mathrm{M}}$ and $\mathbf{x}_{\mathrm{m}}$ respectively) is given by:

$$C_{mech}(\mathbf{x}_{\mathrm{M}}, \mathbf{x}_{\mathrm{m}}) = \frac{1}{2}\sum_{i=1}^{N}\mathbf{U}_i^T\mathbf{K}_i(\mathbf{x}_{\mathrm{M}}, \mathbf{x}_{\mathrm{m}})\mathbf{U}_i \tag{5}$$

where Ui and Ki represents the nodal displacement, and the stiffness matrix of the ith element with respect to the macrostructure of the N number of the elements. The stiffness matrix is taking the form [27]:

$$\mathbf{K} = \int_V \mathbf{B}^T\mathbf{E}\mathbf{B}dV \tag{6}$$

where $\mathbf{E}$ is the element's elastic tensor and $\mathbf{B}$ is the strain displacement matrix. The elastic modulus of the microstructure $\mathbf{E}_{ijqp}$ that is consisting of void and solid material is connected to the elastic tensor of the based solid material $\mathbf{E}_0$ as:

$$\mathbf{E}_{ijqp} = \mathbf{x}_{\mathrm{m}}\mathbf{E}_0 \tag{7}$$

The effective elastic tensor of the microstructure $\mathbf{E}^{\mathrm{H}}$ that is calculated by implementing Eq. (3) is used to make the macroscale of the elemental elastic tensor $\mathbf{E}_{macro}$ with a similar material interpolation scheme but with the difference of adopting the relaxed penalization of the macro design variables. The relaxation and penalization principles are utilized in SIMP in order to solve many problems that face the early version of it such as the non-existence and grayscale [28, 29]. However, these modifications are serious limitations for attaining design with global extrema of the traditional SIMP method [30–32]. This issue will be discussed later in the discussion section, so returning to the formulation part of the research, the elastic tensor $\mathbf{E}_{macro}$ is formulated by penalizing the macro design variable $\mathbf{x}_{\mathrm{M}}$ to power ($p \geq \max[\frac{2}{1-\upsilon}, \frac{4}{1+\upsilon}]$) [33]. Here υ is the Poisson ratio of the solid materials. In this research p is chosen to be 3. The elastic modulus of the macrostructure is taking the final form of:

$$\mathbf{E}_{macro} = (1-\alpha)\mathbf{x}_{\mathrm{M}}^3\mathbf{E}^{\mathrm{H}} \tag{8}$$

where α is an infinitesimal value. By assuming that the actuator is subject to linear strain limits, a spring of stiffness Kin, and a force Fin at the input point A, the generalized model of the mechanically activated compliant mechanism problem is linearly implemented. As shown in Fig. 1, the goal is to maximize the displacement at the output point B.

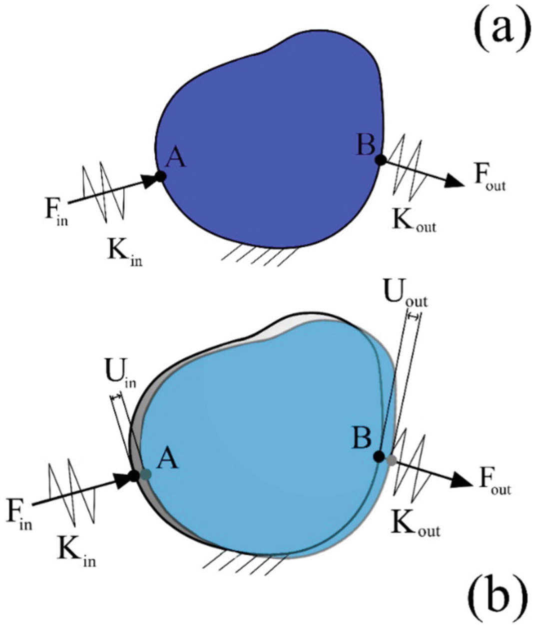

Fig. 1. The soft robotic gripper mechanism design problem

$$\max_{\boldsymbol{\rho}} \ : \ \mathbf{U}_{out}$$
$$\text{s.}t. \ \{\mathbf{KU} = \mathbf{F}$$
$$\int\limits_{\Omega_{dM}} \mathbf{x} \, d\Omega_{dM} \ \leq \ v \ , \ \ \mathbf{x} \in (0, 1] \quad \forall \mathbf{x} \in \ \Omega_{dM} \tag{9}$$

The goal of is to attain porous soft gripper with maximizing the porous robustness to withstand the different loading condition. As such, in this research, we investigated the two cases of maximizing the bulk modulus and maximizing the shear modulus, of the microstructure. Therefore, the optimization is addressing also, the maximization of $\mathbf{E}^{\mathrm{H}}$. The concurrent multiscale optimization algorithm will be:

$$\textit{find} \quad \mathbf{x}_{\mathrm{M}}, \mathbf{x}_{\mathrm{m}} \ \ (\mathrm{M} = 1, 2, .., N_{\mathrm{M}} \, ; \ \mathrm{m} = 1, 2, .., N_{\mathrm{m}})$$
$$\max_{\boldsymbol{\rho}_{\mathrm{M}}, \boldsymbol{\rho}_{\mathrm{m}}} \ : \ \mathbf{U}_{out}(\mathbf{x}_{\mathrm{M}}), \ \ \textit{Cellular stiffness} = \begin{cases} \textit{Bulk modulus} = \mathbf{E}^{\mathrm{H}}_{11}(\mathbf{x}_{\mathrm{m}}) + \mathbf{E}^{\mathrm{H}}_{22}(\mathbf{x}_{\mathrm{m}}) \\ \textit{Shear modulus} = \mathbf{E}^{\mathrm{H}}_{33}(\mathbf{x}_{\mathrm{m}}) \end{cases}$$
$$\text{s.}t. \ \begin{cases} \mathbf{K}(\mathbf{x}_M)\mathbf{U} = \mathbf{F} \\ \mathbf{E}^{\mathrm{H}} = \frac{1}{|V|} \int\limits_{V} \mathbf{E}_{ijqp}(\mathbf{x}_{\mathrm{m}}) \left(\boldsymbol{\varepsilon}^{0(kl)}_{qp} - \boldsymbol{\varepsilon}^{*(kl)}_{qp} \right) dV \end{cases}$$
$$\int\limits_{\Omega_{dM}} \mathbf{x}_{\mathrm{M}} d\Omega_{dM} \ \leq \ v_{\mathrm{M}} \ , \ \ \mathbf{x}_{\mathrm{M}} \in (0, 1] \quad \forall \mathbf{x}_{\mathrm{M}} \in \ \Omega_{dM}$$

$$\int_{\Omega_{dm}} \mathbf{x}_{\mathrm{m}} d\Omega_{dm} \ \leq \ v_{\mathrm{m}} \ , \ \mathbf{x}_m = 0|1 \qquad \forall \mathbf{x}_{\mathrm{m}} \in \ \Omega_{dm} \tag{10}$$

Here, N_{M} and N_{m} stand for the macro- and microscale structures' corresponding element numbers. v_{M} and v_{m} are the volume fraction of the design variable $\mathbf{x}_{\mathrm{M}}$ and $\mathbf{x}_m$ within the macro and micro design domains (Ω_{dM} and Ω_{dm} respectively).

2.1 Sensitivity Analysis and Optimization Method

The sensitivity analysis is given in equation, taking into account that the mechanical loading vector F is design independent in our linear analysis (11)

$$\frac{\partial C}{\partial \mathbf{x}} = \mathbf{U}_{in}^{T} \frac{\partial \mathbf{K}}{\partial \mathbf{x}} \mathbf{U}_{out} \tag{11}$$

while $\frac{\partial \mathbf{K}}{\partial \mathbf{x}}$ is only depending of the macroscale, therefore; the derivative of will take ethe form:

$$\frac{\partial \mathbf{K}}{\partial \mathbf{x}_{\mathrm{M}}} = \int_{|\Omega_{\mathrm{M}}|} \mathbf{B}^{T} \frac{\partial \mathbf{E}^{\mathrm{H}}(\mathbf{x}_{\mathrm{M}})}{\partial \mathbf{x}_{\mathrm{M}}} \mathbf{B} \ d\Omega_{\mathrm{M}} \tag{12}$$

The microstructure objective function is independent of the macrostructure design variables $\mathbf{x}_{\mathrm{M}}$, and only depending on the microstructure $\mathbf{x}_{\mathrm{m}}$ [34]. Therefore, the sensitivity of the homogenized material's elastic tensor $\frac{\partial \mathbf{E}^{\mathrm{H}}(\mathbf{x}_{\mathrm{m}})}{\partial \mathbf{x}_{\mathrm{m}}}$ is taking the form:

$$\frac{\partial \mathbf{E}^{\mathrm{H}}(\mathbf{x}_{\mathrm{m}})}{\partial \mathbf{x}_{\mathrm{m}}} = \frac{p}{|\Omega_m|} \int_{\Omega_m} \left(\mathbf{x}_{\mathrm{m}}^{p-1}\right) \mathbf{E}_{ijqp}^{0} \left(\boldsymbol{\varepsilon}_{qp}^{0(kl)} - \boldsymbol{\varepsilon}_{qp}^{*(kl)}\right) d\Omega_m \tag{13}$$

The macrostructure in this work is optimized with the SIMP approach, and the microstructure with the ESO method. This hybrid approach to optimization made it possible to produce solid and understandable design concepts while also drastically lowering the computing expense. The optimality criteria approach is also used to update the design variables[35, 35]. In order to ensure that solutions to the topology optimization problem exist and that the checkerboard problem doesn't emerge, a sensitivity filter is included to alter the sensitivities. $\dot{C}(\mathbf{x}_{\mathrm{M}})$ and $\dot{C}(\mathbf{x}_{\mathrm{m}})$ as follows:

$$\hat{\dot{C}} = \frac{\partial C}{\partial \mathbf{x}_e} = \frac{1}{\mathbf{x}_e \sum_{f=1}^{N} H_f} \sum_{f=1}^{N} H_f \mathbf{x}_f \frac{\partial C}{\partial \mathbf{x}_f} \tag{14}$$

where H_f is the convolution operator to perform the modification, $\mathbf{x}_e$ is the design variable at which the sensitivity is calculated, and $\mathbf{x}_f$ [27, 27]. The H_f is defined as:

$$H_f = r - dist(e,f), \ \{f \in N | dist(e,f) \leq r\} \tag{15}$$

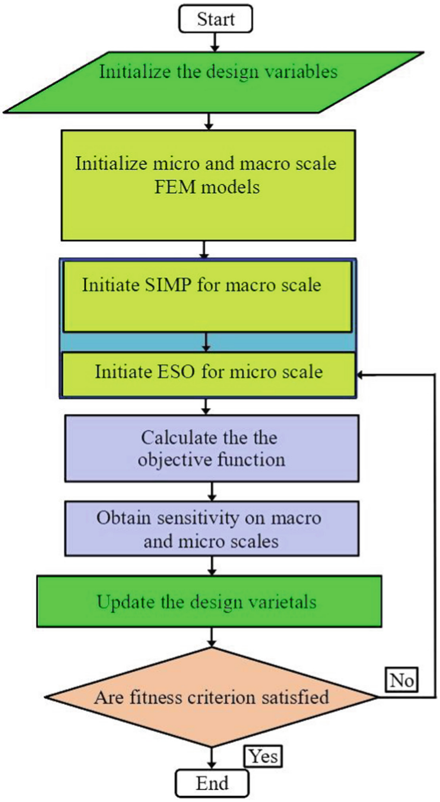

Fig. 2. Flowchart of concurrent multiscale optimization for soft gripper

After modifying the sensitivity, the following is a heuristic updating technique:

$$\mathbf{x}_e^{updated} = \begin{cases} \max(0, \mathbf{x}_e - \varepsilon) \ \textit{if} \ \ \mathbf{x}_e B_e^{\omega} \leq \max(0, \mathbf{x}_e - \varepsilon) \\ \max(0, \mathbf{x}_e + \varepsilon) \ \textit{if} \ \ \mathbf{x}_e B_e^{\omega} \geq \max(1, \mathbf{x}_e - \varepsilon) \\ \mathbf{x}_e B_e^{\omega} \qquad\qquad\quad \textit{Otherwise} \end{cases} \tag{16}$$

where ε denotes a positive search step. Moreover, ω which is equal to 1/2 denotes a numerical damping coefficient, and B_e denotes the optimality condition:

$$B_e = -\frac{\partial C}{\partial \mathbf{x}_e} \bigg/ L\frac{\partial V}{\partial \mathbf{x}_e} \tag{17}$$

where L here is a Lagrangian multiplier, and $\frac{\partial V}{\partial \mathbf{x}_e}$ is the volumetric topological derivative. The general algorithm for concurrent multiscale and hybrid topology optimization for soft robotic gripper is illustrated in Fig. 2.

3 Numerical Examples and Discussion

In this section, we are investigating several examples of soft gripper. The first model is having 80 and 80 mm in the x and the y directions (As shown in Fig. 3 (a)). The microstructure has 100 by 100 elements in the x and y directions. The volume faction condition for microscale was 0.3, and 0.4 for the macroscale. For all cases, elastic tensor for solid material ($\mathbf{E}_0$) is given in Eq. (18).

$$\mathbf{E}_0 = \begin{bmatrix} 3 & 1 & 0 \\ 1 & 3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{18}$$

The first case of study is maximizing the bulk modulus [37] of the microscale ($\mathbf{E}^{\mathrm{H}}_{11} + \mathbf{E}^{\mathrm{H}}_{22}$ for 2D case). The microscale design is shown in Fig. 3 (b) and (c). The macroscale design is shown in Fig. 3 (d). To address the shear resistance maximization of the microscale, shear modulus ($\mathbf{E}^{\mathrm{H}}_{33}$) is maximized for the problem mentioned earlier. The microscale design is shown in Fig. 3 (3) and (f). The macroscale design is shown in Fig. 3(g). The second macro design domain of 80 and 160 mm in the x and the y directions (As shown in Fig. 3 (h)). The gripper design results with maximizing the bulk modulus are shown in Figs. 3 (i), (j),and (k). For the case of maximizing the shear modulus, the results are presented in Figs. 3 (l), (m), and (n).

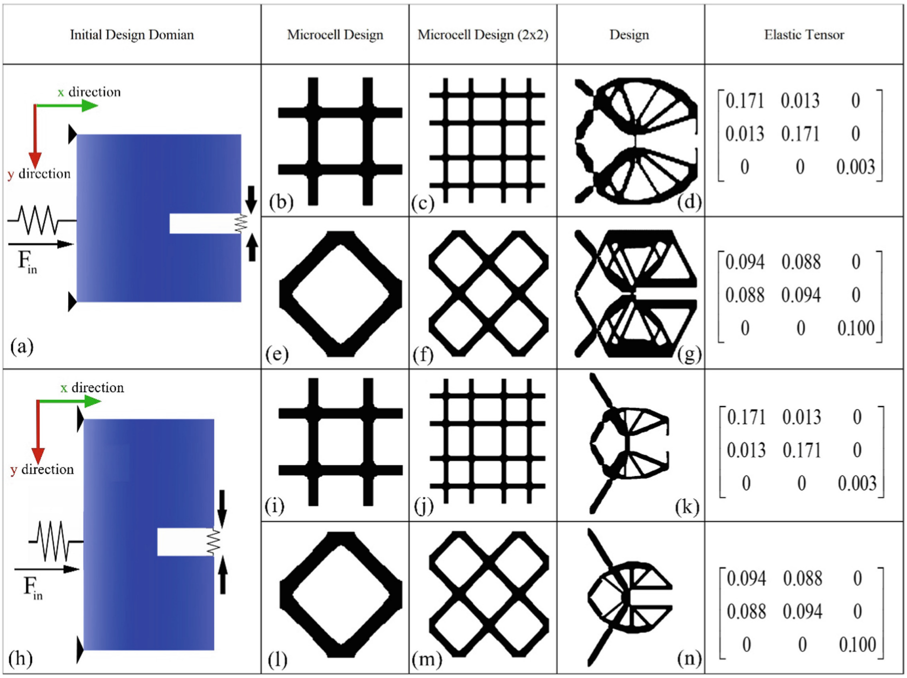

Fig. 3. Concurrent multiscale designs cases

In order to evaluate the computational cost of the suggested hybrid (SIMP-ESO) topology optimization method compared to the topology optimization using the SIMP method, we performed SIMP topology optimization for the second example (i.e., Fig. 3 (h)). The iteration numbers of the SIMP and hybrid (SIMP-ESO) methods are shown in Fig. 4. The results showed attaining robust design in a shorter time for the suggested hybrid method compared to the SIMP method (almost 3 times faster for the Hybrid topology optimization method).

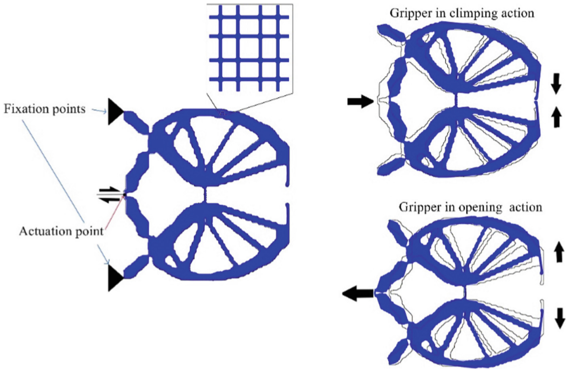

Fig. 4. Concurrent multiscale design of first numerical case of soft robotic in action

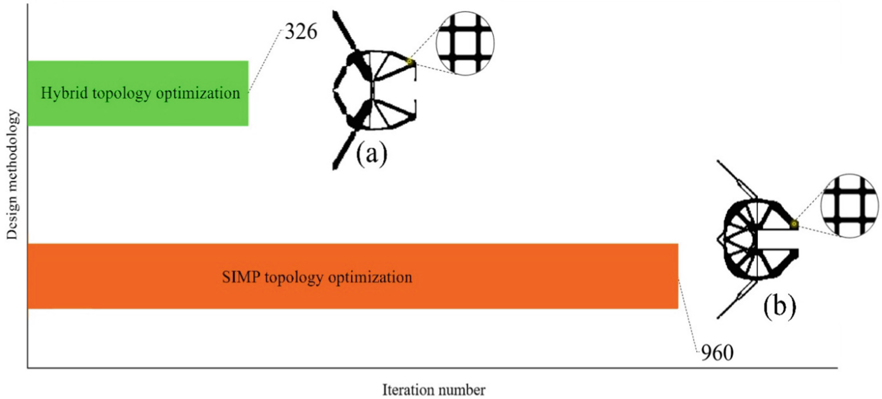

Fig. 5. The number of iterations for the hybrid topology optimization and SIMP method.

The output displacement ($\mathbf{U}_{out}$) of our hybrid multiscale concurrent topology optimization (as shown in Fig. 5 (a)), also showed better results (1.2 times better) than using SIMP method alone (as shown in Fig. 5 (b)).

It is important to mention that Bendsoe and Sigmund [38] after performing a series of investigations with DOCO and the SIMP method, stated that when modeling the problem of the compliant mechanism using linear analysis (which is the analysis that is used in this research for all cases) often gives bad or useless designs compared to the results that obtained with considering the nonlinear analysis instead. Moreover, they emphasized that for using linear analysis, in the best-case scenario, one only gets erroneous findings; in the worst-case scenario, the results are useless for a compliant mechanism. Consequently, it is imperative (As they stated) for designing compliant mechanisms with topology optimization, to adopt geometrically non-linear finite element modeling [38].

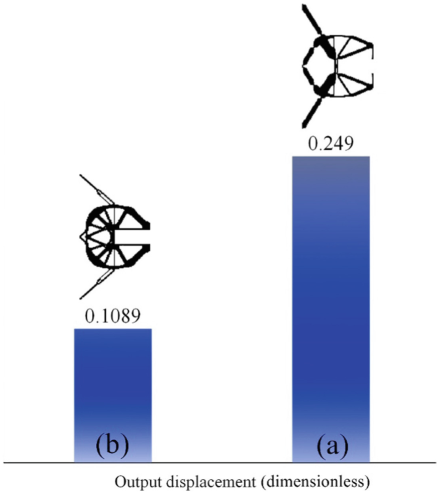

Fig. 6. The comparison of the output displacement for the suggested hybrid topology optimization and SIMP method.

The numerical examples that Bendsoe and Sigmund used, were built considering a simplistic gradient descent algorithm in mind (i.e., optimality criteria method (OCM)). The OCM's drawback is that it can fall into local extremum easily, therefore; careful attention to the gradient decent parameters is a must [20, 30]. Later several researchers make use of the method of moving asymptotes (MMA) [39, 40]. It is a general-purpose algorithm that can accommodate different kinds of optimization problems. It is based on a convex approximation that is appropriate for topology optimization, but the asymptote and move limitations have a significant impact on how effective it is [41]. Due to their nature, OCM and MMA methods are single-point search algorithms, which make them fall easily into local minima [42], especially with increasing the penalization power of the SIMP method. These points necessitate the investigation of the cause of nonlinear analysis promotion under further scrutiny. As such, after performing several investigations, our research has proved the first section of Bendsoe and Sigmund's statement, that the linearized modeling of maximizing the displacement as an objective function for attaining a compliant mechanism will give questionable design (as shown in Fig. 6 (b)).

In a previously performed research, a nonlinear finite element modeling of piezoelectric gripper was successfully attained [43]. And this is validating the second part of the statement of Bendsoe and Sigmund. However, in this research, we are showing robust design with good hinges formations (Fig. 6 (a)) in the case of hybrid topology optimization. From the results, we deduce that the linear analysis is not the problem of not attaining good hinges for compliant mechanism design. Also, we extend our deduction that in the nonlinear analysis, the nonlinearity consideration is overcoming the huge alteration of the design variables by the penalization (and less severity in the mesh independency filters).

In Fig. 7, the Young modulus of elasticity is jumping as a function of third order so it will impact values of nodal displacements in the scope of linear elastic finite element analysis (especially with the use of bilinear element). As such, rigid elements (the design variables become unity) will aggregate around the hinges that should be existed. In non-linear analysis, the iterative methods are sensitive to the coupled analysis, therefore; the small fields (due to the low value of the penalized design variables) will appear strongly.

While in our hybrid multiscale topology optimization, the optimization is starting with a high value for the elastic tensors and then gradually decreases for all elements. This is put the macro design variables in a situation that is similar to modified Rational Approximation of Material Properties (RAMP) optimization. As such, the solution did not fall into local minima. Under these results, we deduce that the key element of the failure that the SIMP method is facing for the displacement control problems is in the method itself, and not in the objective or the finite element analysis. Moreover, the SIMP method can give great results if associated with some problem-related modifications, and parametrizations such as using ESO for concurrently designing the microscale in this research.

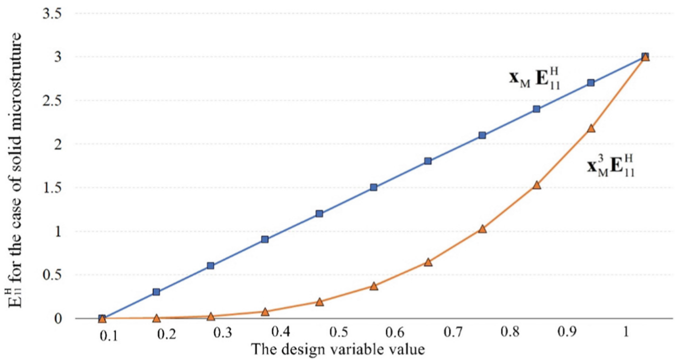

Fig. 7. The effect of the penalized design variable on the elemental young modulus of elasticity.

4 Conclusions

The numerical examples demonstrated that the microscale design responded well to the spatial configuration and the design domain's boundary conditions on both macro and microstructure. In relation to macrostructure design, the spatial arrangements for the various scenarios showed an elaborated method for distributing strain energy on the macroscale. Microstructure, on the other hand, has shown optimized material distribution to maximize the moduli of elasticity in the case of optimizing the bulk modulus of elasticity. For maximizing the shear modulus, the material distribution showed a good response to maximize the overall response especially the shear resistance (by increasing E33). Our hybrid approach of using SIMP for macroscale design and ESO for microscale design simultaneously allowed us to achieve good designs while also significantly reducing the computational cost. As a result, the suggested design process has the potential to create new, innovative, lightweight, porous soft robotic gripper designs that are both durable and elastically flexible.

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